

# **AIRCRAFT ACCIDENT SURVIVABILITY: ROTARY WING AIRCRAFT**

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## **ABSTRACT**

The intent of this paper is to explore the premise of aircraft accident survivability focusing primarily on military rotary wing aircraft. Human tolerance limits to impact forces and post-crash factors will be examined. Current trends and technology improvements leading to an increased potential for survivability will be discussed and crashworthy design features integrated into advanced platforms will be reviewed.

Primary factors of aircraft accident survivability with respect to rotary wing applications, consisting of crashworthy design, human tolerance limit estimates, post crash environments, and general survivability factors shall be explored. While firm human tolerance data is not available due to difficulties of live research, the dynamic nature of mishap events and physical differences among aviators, tolerance estimates are utilized in crashworthy design to mitigate the damaging effects of crash loads in excess of occupant limits. Methods to reduce impact forces experienced by occupants will be reviewed, and recent improvements in helicopter airframe design from the systems perspective will be introduced. Crashworthiness and survivability are essential areas of concentration and are subject areas of rising importance within the aviation industry. While perhaps not as mathematically, scientifically or historically defined or documented as fields such as structures and dynamics, crashworthiness and survivability will likely come to the forefront of aviation in coming years.

## **INTRODUCTION**

Accidents are inherent in aviation. Many have noted that the only method of completely mitigating aviation related accidents is to cease all flying operations. The former statement is generally viewed as a less than attractive option for those affected by the aviation sector; thus, the fields of aviation safety, crashworthiness, human factors, structures and countless others have been tasked with creating airframe environments that are more conducive to survivability than have been their rotary-wing predecessors. Why the emphasis on rotary-wing survivability and crashworthy design? Escape is a unique challenge for rotary wing applications. [1]

## **A NEED IDENTIFIED**

The U.S. Army Transportation Research Command (now the Aviation Applied Technology Directorate, U.S. Army Aviation Research and Technology Activity, U.S. Army Aviation Systems Command) recognized the need for initiating a long-range research program, assessing all aspects related to aircraft safety and survivability. Initiated in 1960, the program examined issues concerning occupant survival in aircraft crashes and the relationships between structural failures, crash forces, fires and injuries. The data collected and lessons learned from the research served as the basis for the design criteria included in MIL-STD-1290, the Army's original version of "Light Fixed- and Rotary-Wing Resistance" standard. Continued research and development has

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resulted in the establishment of the Aircraft Crash Survival Design Guide, a widely referenced tool for crashworthy aircraft design. [2]

## **A SYSTEMS APPROACH**

As of late, crashworthy design has been recognized as a necessary component of the systems safety process in prototype and new helicopter design. Legacy platforms are commonly retrofitted with crashworthy design features, thereby increasing occupant safety to an extent, given airframe limitations; however, the greatest benefit to survivability may be realized when crashworthy design is implemented early in the design process as a systems approach. Designing for the positive interaction of all elements of the airframe to improve survivability is essential.

Crashworthy design features are not limited solely to energy absorbing seating and occupant restraint systems. Combined efforts of safety specialists, numerous support competencies, crash impact and survivability studies and available materials and technologies has led to numerous advances in crashworthy design. In an attempt to minimize G-forces on occupants, all elements in the load path must absorb impact energy. Load path elements consist of: the aircraft structure, energy attenuating landing struts, energy absorbing seats, and occupant restraint systems. Appropriate aircraft structure design incorporates the capability to absorb energy through controlled deformation. Designing a sturdy, smooth understructure can prevent an abrupt deceleration, noted in low angle impacts on soft terrain. Energy attenuating landing struts serve as a key component of the load path, assisting in the dissipation of a portion of the ground impact forces prior to reaching the occupied volume of the airframe.

Ground impact loads remaining following dissipation by the aircraft structure and energy attenuating landing struts are transmitted to the energy absorbing seats and occupant restraint systems, and then to the occupants. Redundant multiple load paths provide reduced vulnerability and improved crashworthiness [3]. A primary goal of the systems approach to crashworthy design is not to exceed the limits of human tolerance upon impact, when possible. Given the dynamic nature of the crash environment and numerous uncontrollable factors, this goal may not always be attainable; however, must be attempted.

Additional aspects of the systems design are focusing on de-lethalizing aircraft structures and maintaining a livable volume within the occupant's immediate vicinity. Providing post-crash fire retardation or elimination devices, emergency egress lighting, and survival equipment to occupants for emergency use, such as breathing devices and flame retardant clothing are all essential components of the systems approach to crashworthy design for survivability. [1]

## **SURVIVABILITY AND CRASHWORTHINESS**

In general, crashworthiness refers to “the capability of an aircraft and its subsystems such as seats, restraints, landing gear, etc. to protect its occupants during and after a crash. The amount of protection that is afforded by the aircraft will depend greatly upon the amount of thought that went into crash survivability during its original design [1].” Crashworthy seating initiatives have led to the incorporation of energy attenuating crew and troop seats in numerous military rotary wing platforms, via retrofit programs, improving crashworthy qualities of aging aircraft.

According to the Aircraft Crash Survival Design Guide, a survivable accident is defined as, “an accident in which the forces transmitted to the occupant through the seat and restraint system do not exceed the limits of human tolerance to abrupt accelerations and in which the structure in the occupant’s immediate environment remains substantially intact to the extent that a livable volume is provided for the occupants throughout the crash sequence.” Thus, relative to the context of this paper, survivability will be defined as

preserving tolerable deceleration forces and maintaining an occupiable post crash volume consistent with life.

While mishap scenarios and crash pulses differ greatly, crash decelerations typically involve a combination of positive  $G_z$  (eyeballs-down) and positive transverse  $G_x$  (eyeballs-out) forces. The combination of forces is due to the horizontal and vertical components of the velocity vectors along the flight path. Figure 1 illustrates the orientation of forces acting on and experienced by the body.

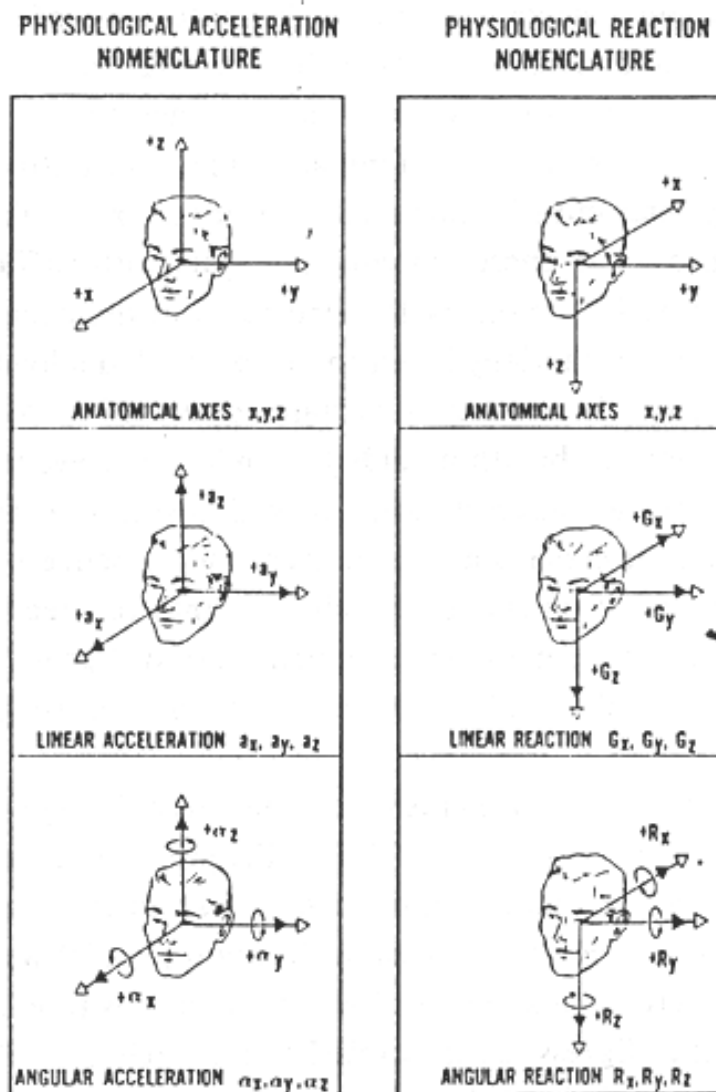


Figure 1. Accelerative forces on the body. [1]

## HUMAN TOLERANCE LIMITS

Estimated human tolerance limits have been developed based on experiments studying human response to ejection, parachute, and rocket powered sled trials. Noteworthy rocket powered sled trials were conducted by Colonel John Stapp in the 1950s. Additional data stemming from outcomes of human accidents, animal and cadaver studies, utilization of anthropometric test dummies and mathematical computer models have provided further insight to human tolerance limits, enabling gaps in previously determined estimates to be bridged.

Human tolerance to deceleration is a function of various factors, including: acceleration direction with respect to the body, acceleration duration, rise time (rate of G onset), acceleration magnitude, type of seat and restraint system, distribution of force over the body, secondary impact of body parts with aircraft, and physical characteristics of the aviator. While separating these factors is not feasible, researchers have determined “that the longer the duration, the greater the magnitude, or the higher the rate of onset, the less likely a person is to survive [4].” Improper utilization of the seat and restraint system can lead to increased load limits experienced by the aircrew. Loose or improperly secured restraints and improperly dialed in variable load energy attenuating seats, or seats without ample stroking distance (i.e. toolbox under the seat) can also lead to increased injury potential for the occupant.

Estimated human tolerance limits, for occupants restrained by four or five point restraint systems, for whole body impacts are noted in Table 1 and regional body impact tolerance limits are displayed in Table 2. Beyond the noted limits, significant injury is anticipated to occur. Again, only estimated tolerance limits are

available, as human tolerance to deceleration is a function of a range of dynamic factors, distinctive to individual aircrew members and mishap scenarios.

**Table 1. Deceleration Force Tolerance Limits, Whole Body Impacts\***

Position	Limit	Duration
Eyeballs-out (-G <sub>x</sub> )**	45 G	0.1 sec
	25 G	0.2 sec
Eyeballs-in (+G <sub>x</sub> )	83 G	0.04 sec
Eyeballs-down (+G <sub>z</sub> )	20 G	0.1 sec
Eyeballs-up (-G <sub>z</sub> )	15 G	0.1 sec
Eyeballs-left or Eyeballs-right (+ / - G <sub>y</sub> )	9 G	0.1 sec

\*Fully restrained subjects exposed to whole-body impact at up to 250 G/sec onset rate. Injury known to occur if exceeded.

**Table 2. Regional Impact Forces Known to Cause Bone Fracture or Concussion**

Body Area	Force	Duration
Head (frontal bone, 2" diameter application)	180 G	0.002 sec
	57 G	0.02 sec
Nose	30 G	*
Maxilla	50 G	*
Teeth	100 G	*
Mandible	40 G	*
Brain (concussion)	60 G	.02 sec
	100 G	.005 sec
	180 G	.002 sec

\*Duration figures not available.

The duration of the forces and the rate of onset can significantly alter human response. The body tends to act as porcelain under short duration exposures with high onset rates. The skeletal system is vulnerable under such conditions. Similarly,

the human body responds more like a hydraulic system in longer exposures with a slower rate of onset, allowing a more elastic response. Consciousness, for example, can be maintained up to 150Gs if the duration is short. Research has indicated, “at about 45 Gx, the heart rotates in the thorax, causing intimal tears of the aorta. As we cannot restrain the heart, 50G is the upper limit of Gx tolerance. A properly restrained human could theoretically survive a deceleration from 150mph to a dead stop in 0.25 sec [4].”

With respect to survivability determinations, the following guidance is provided, “if the calculated crash forces on the airframe exceed the human tolerance limits by a factor of two or more, survivability is unlikely. If the limits are exceeded by a factor of 0.5, survivability is doubtful.” Further guidance indicates that survivability can be dependent on alternate factors as discussed above, if the limits are exceeded by 0.25 or less. Survivability is anticipated if the human tolerance limits are not exceeded; however, various external factors contribute to the ultimate determination of survivability. [4]

## **SURVIVABILITY FACTORS**

Factors affecting survivability are organized into five distinct groupings consisting of; the container, restraints, environment, energy absorption, and post crash factors. Each factor, combined with human tolerance data, contributes to the overall potential for survivability in rotary-wing mishap scenarios.

The container constitutes the airframe and its internal components. The ideal container will allow for habitable space to be maintained during and following the crash pulse. In reality, rotary-wing fuselages typically exhibit elastic behaviors and blade penetration into the occupiable structure may occur. Cockpit and internal

structures collapse and pedals and controls can entrap occupants. Sub-floor upheavals and transmission collapses have been documented and container rollover has been noted as a common occurrence. Containers that exhibit collapse, disintegration, penetration or failure to preserve a habitable volume may produce or exacerbate injuries.

Restraint systems are utilized to prevent occupants, cargo and components from being released or thrown during decelerative episodes. It has been postulated by some in the pre-crashworthy airframe design era, “if the human body is rigidly attached (restrained) to a decelerating vehicle, the deceleration sustained by the human skeletal structure is about equal to that of the vehicle [5].” This notion; however, may not hold true in rotary-wing aircraft utilizing redundant load limiting devices, such as a load path to dissipate harmful G loadings prior to reaching the occupant. If crashworthy systems function as intended, the crash forces on the airframe should be higher than the deceleration experienced by the human.

The capability of restraint systems to function as injury mitigating devices is dependant on various factors. Do floor attachment bolts support the strength (G load) of the seat, which in turn supports the strength of the restraint system webbing (typically designed to withstand a 10,000 pound load)? Is the restraint system webbing torn, worn or in need of repair or replacement? Are restraints properly secured, or has the crewmember secured the restraint loosely or failed to secure the restraint entirely? Do missions allow the aircrewmember to remain restrained at all times in a crashworthy system?

Submarining and dynamic overshoot are issues commonly associated with loose restraint systems. Submarining occurs when the occupants’ hips rotate under the lapbelt as a result of forward

loading exerted by deceleration of the thighs and lower legs in combination with upward slippage of the restraint. Dynamic overshoot is an amplification of decelerative forces above the crash pulse forces, experienced when the aircraft has begun deceleration before the occupant impinges on his restraint system. Dynamic overshoot may also be experienced by unrestrained portions of the body, which come into contact with components in its path. [1]

The environment in which the mishap occurs is an additional factor influencing survivability. The container environment, such as strike distance between a restrained occupant and airframe components can affect survivability estimations. It should be noted that elastic deformation during the impact phase could lead to the appearance of a survivable crash, while in actuality, the occupiable volume at impact may have been reduced drastically, without traces of witness marks.

The appropriateness of material choices, garment selection, helmet usage and survival equipment supplied for the mission can contribute to or diminish the chances of occupant survivability in a mishap setting. Additional cockpit/fuselage environmental features include fabrication materials utilized in the manufacture of the airframe and aircraft components. Toxicological properties of substances in post crash fires may incapacitate aircrews, reducing chances of survival. Finally, the egress environment and design for access to egress is key. The speed with which aircrews can successfully egress the downed aircraft is an essential component of survivability. An environment conducive to expedient emergency egress will likely increase the chances of occupant survivability, while ineffective egress design can lead to unparalleled consequence. [4]

The fourth factor affecting survivability is energy absorption, as

discussed previously with respect to load path development. Energy absorption devices, such as honeycomb construction, expendable space and metal, aircraft structure, landing struts, stroking seats, and occupant restraint systems can affect the likelihood of survival following an aircraft accident. Energy attenuating (crashworthy) crew seats displace downward and slightly forward in response to decelerative forces, typically initiating stroke at 14.5 G. The displacement not only absorbs energy in an attempt to maintain deceleration limits within the estimated realm of human tolerance, but also may have potentially saved aircrew from decapitation via blade strike in the cockpit. [1]

Finally, post crash factors are discussed with respect to survivability. A myriad of post crash factors affect occupant survivability, such as fire, poor communications, inadequate rescue capabilities, water survival requirements, and training problems. Said factors can all have a detrimental effect on the ultimate outcome, yet fire has been coined the most important post crash factor affecting survivability. In the event of a post crash fire, the ability to rapidly egress becomes the essential survival factor. While burns can be injurious and at times fatal, suffocation or breathing smoke and toxic fumes are notably more hazardous, and are more often associated with cause of death in a fire than are burns. [6] "Along with the direct thermal effects of fire, the attendant hazards from products of combustion must be recognized. Toxic gases, including carbon monoxide, cyanide, phosgene, and acrolein may all contribute to the injury or be fatal themselves. Carbon dioxide levels will also rise, promoting reflex hyperpnea. Particulate matter and smoke can not only interfere with breathing, but also decreases visibility, hindering egress and rescue efforts [1]."

When an occupant suffers incapacitating effects, the escape limit is achieved. The escape limit is controlled by what the occupant feels (temperature), breathes (toxic gases) and sees, or does not see (escape routes, hatches). Human tolerance limits define bodily reactions to the factors affecting the escape limit.

A number of recommendations have been introduced to increase survivability in response to post crash factors. Providing a sufficient means of egress, designing aircraft seats and interiors to reduce current hazards of pyrolyzation of synthetics, designing crashworthy fuel systems and cradling flammable fluid systems to provide maximum impact protection are among the suggested practices. Additional recommendations include incorporating the use of crash resistant self-sealing fuel cells, installing fuel lines with breakaway valves designed to self isolate following impact, separating fuel systems from likely ignition sources and providing proper flight gear/clothing, rated for fire protection. [4]

## **TRAINING**

Risk can be further mitigated via incorporating procedures and training for users. Numerous studies have noted that most fatalities are linked to the inability to egress the aircraft, not due to crash trauma sustained in the mishap scenario. Accordingly, ditching and emergency egress drills are required and practiced in operational squadrons, as designated. In addition to egress training and post crash survival training, aircrew must be trained on proper utilization of crashworthy equipment, such as seat and restraint utilization. The most superior protective equipment is worthless if not properly utilized or if ignored completely.

## **RECENT IMPROVEMENTS**

Recently acquired Sikorsky products exemplify the current trend of incorporating crashworthy design into the systems safety process. While Sikorsky products are referenced herein, the exclusion of additional manufacturers is due solely to available research at the time of print of this effort. According to the United States Naval Flight Surgeon's Manual, "The SH-60B Sea Hawk, one of the latest Navy helicopter types to join the fleet, has come closest to applying a total systems concept to crash survival. Crashworthiness was an important part of the aircraft design and the benefits derived from this forethought have resulted in the survival of crewmembers in severe crashes that would have been otherwise nonsurvivable. The Sea Hawk has energy attenuating landing struts; a box type subfloor structure that can maintain its integrity during a potentially survivable crash; impact resistant fuel cells to reduce the possibility of fire; inflatable exterior fuselage flotation bags, and energy absorbing seats in the cockpit and aft compartment." [1]

An additional example of survivability and crashworthy design features implemented as part of the system concept is evidenced in the S-70A International Black Hawk Helicopter. Design features consist of: energy absorbing landing gear, load limiting crew and troop seats (armored pilot and copilot seats), crashworthy fuel cells, jettisonable cockpit doors, high mass components retained in 20/20/18G crash conditions (delethalizing aircraft structures), large cabin doors and windows designed to potentially enable improved access to egress, and self-sealing fuel tanks and lines. Additional features, such as; spall resistant windshields and cockpit structure, redundant control systems and fail-safe tail rotor controls, triple

redundant hydraulic and electrical systems, wire cutters, and improved transmission system are among the advancements intended improve survivability estimates for occupants. The S-70A has presented numerous survivability and crashworthy design features based on feedback and lessons learned from earlier model Black Hawk operators and mishap reports. [7]

## CONCLUSIONS

Primary factors of aircraft accident survivability with respect to rotary wing applications, consisting of crashworthy design, human tolerance limit estimates, post crash environments, and general survivability factors were explored. While firm human tolerance data is not available due to difficulties of live research, the dynamic nature of mishap events and physical differences among aviators, estimates are utilized in crashworthy design to mitigate the damaging effects of crash loads in excess of occupant limits. Methods to reduce impact forces experienced by occupants were reviewed, and recent improvements in helicopter airframe design from the systems perspective were introduced. Crashworthiness and survivability are essential areas of concentration and seemingly are subject areas of rising importance. While not as mathematically and scientifically defined as fields such as structures and dynamics, crashworthiness and survivability will likely come to the forefront of aviation in the coming years. After all, ensuring that aviators complete missions successfully is essential to all involved.

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## **BIOGRAPHY**

Elizabeth Motley is a Crashworthy Systems Engineer for the Human Systems Department, Naval Air Warfare Center Aircraft Division (NAWCAD), located in Patuxent River, MD. Elizabeth graduated from Virginia Polytechnic Institute and State University (Virginia Tech) in 2002 with a B. S. in Industrial and Systems Engineering, concentrating in Human Factors. In April 2004, Elizabeth received the Aviation Safety certificate from University of Southern California. In February 2005 she completed coursework toward the Aviation/Aerospace Safety Systems certificate from Embry Riddle Aeronautical University. Elizabeth is currently pursuing a Masters of Aeronautical Science degree from Embry Riddle Aeronautical University. Elizabeth is heavily involved in Aircrew Escape Systems and Crashworthy Fleet Support Team (AESFST) and Life Support Systems Fleet Support Team (LSSFST) initiatives, as well as additional crashworthy related engineering assignments at Patuxent River Naval Air Station.